JPRS: 4382

6 February 1961

SELECTED TRANSLATIONS FROM "YADERNAYA GEOFIZIKA"

(NUCLEAR GEOPHYSICS)

Distributed by:

OFFICE OF TECHNICAL SERVICES
U. S. DEPARTMENT OF COMMERCE
WASHINGTON 25, D. C.

U. S. JOINT PUBLICATIONS RESEARCH SERVICE
1636 CONNECTICUT AVENUE, N. W.
WASHINGTON 25, D. C.

F O R E W O R D

This publication was prepared under contract by the UNITED STATES JOINT PUBLICATIONS RESEARCH SERVICE, a federal government organization established to service the translation and research needs of the various government departments.

JPRS: 4382

CSO: 1431-S

SELECTED TRANSLATIONS FROM "YADERNAYA GEOFIZIKA" (NUCLEAR GEOPHYSICS)

[Following is the translation of selected articles from the book Yadernaya geofizika (Nuclear Geophysics), A. P. Kalantarov, Chief Editor; Moscow, State Scientific and Technical Publishing House of the Petroleum and Mineral-Fuel Industry, 1959. The authors and page numbers of the individual articles are given along with their titles within the report.]

TABLE OF CONTENTS

THE PREVENTION OF WATER-PETROLEUM CONTACT BY THE METHOD OF INDUCED ACTIVITY OF SODIUM IN CONDITIONS ENCOUNTERED IN PETROLEUM DEPOSITS OF AZERBAYDZHAN

-USSR-

[Following is the translation of an article by S.M. Aksel'rod in "Yadernaya Geofizika" (Nuclear Geophysics), Moscow, 1959, pages 100-102.]

Under the conditions of the Azerbaydzhan petroleum deposits, the prevention of water-petroleum contact in cased bore wells poses serious problems connected with the specific peculiarities of these deposits: the low mineral content of the stratified water, and the heterogeneity and high clay content of water pockets.

Due to the indicated characteristics of the Azerbaydzhan petroleum deposits, the neutron gamma-method (NGM) does not afford a means for preventing water-petroleum contact.

At the same time, under the conditions of the upper region of the tapped layer, which contains stratified waters of a salinity on the order of 11° Be (Beaume) (110 grams/liter), the induced sodium activity method (NA -- navedennaya aktivnost' natriya) has a stronger effect at water-petroleum contacts than the NGM, and gives positive results.

Bore-well probes by the NA method are performed in the following manner: Each test point is irradiated by a $(5-10)10^6$ neutrons/second neutron source for five hours; the measurement of induced activity is then carried out for 15 hours.

Petroleum content estimates according to induced activity values are made 14-15 hours after the completion of irradiation.

In order to reduce the time necessary for bore test-

ing, three test points are irradiated simultaneously by means of three sources of approximately equal radioactivity. Measured values of the induced activity are referred to a single source radioactivity value.

The gamma-activity is measured by means of the standard radiometric apparatus with discharge counters. The placement of the assembly probe opposite the irradiated point is accomplished roughly by means of guide markings, and then refined in the initial measurement in accordance with the maximum measured γ-radiation.

Testing by the NA of sodium method has provided a means of estimating the situation as regards water-petroleum contact in a number of bore wells.

For example, in bore No 521 of the Ordzhonikidzeneft' Petroleum Industry Installation (Neftepromyshlennaya Ustanovka) which has a 6" lining column, the IVth level of the Surakhan suite was studied; according to electrometric measurements carried out in 1936, the oil-bearing strata in the bore lay in the intervals of 740-742, 744-747, and 750-753 meters, all having approximately the same porosity.

The study consisted of irradiation at five points (738.5, 740, 742, 750, 753.5).

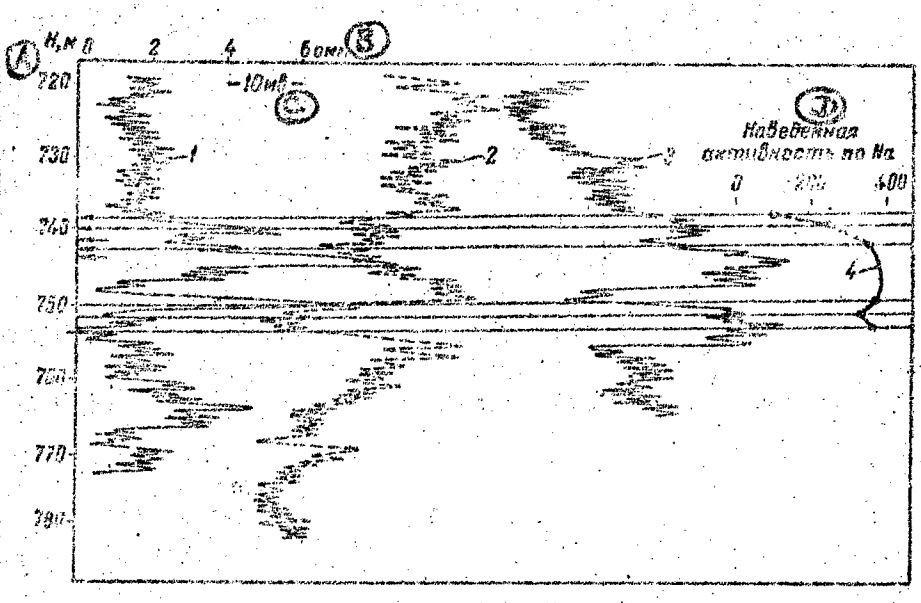
As is evident from the induced radioactivity curves (see Figure), obtained from the 15-hour measuring period, the lowest induced activity corresponds to the upper portion of the topmost layer (740 meters); the middle portion of the upper layer exhibited greater induced radioactivity. The other points are characterized by maximum induced radioactivity values.

The effect determined by the ratio of the difference between the maximum and minimum values to the minimum induced radioactivity values amounts to 300% in the given bore hole.

Thus, from the results of the measurements it is possible to conclude that only the upper portion of the topmost layer is oil-bearing.

This was confirmed by bore perforations.

As was indicated above, the field of application for the NA method under the conditions of the Apsheronskiy Peninsula is limited to several levels of the upper strata. This makes for additional difficulties in testing; this is connected with the fact that most of the bore wells tapping the indicated strata have large (8-10") casing tube diameters.



The Results of Industrial Geophysical Studies of Bore-Well No 521 of the Ordzhonikidze Oil Fields.

A = Depth, in meters.
B = Ohm-meter-millimeter^2 (volume resistivity units).
C = Millivolts.
D = Induced Na radioactivity.
1 = Calibration resistivity log, (Sonde No 6M2A).
2 = S.P. (Self-Potential) log.
3 = NGK log.

In such cases, liquid is pumped out of the bore hole in order to increase the effect, and the testing is done in the empty bore. When the removal of liquid from the bore is impossible, the latter is replaced by water of lower salinity than that occuring below the petroleum level, such as sea water. Such measures serve to improve logging accuracy.

It is necessary to note that the effects obtained in strata studies usually do not exceed 70%; this fact lessens the reliability of conclusions based on such studies.

The weak effects may be theoretically explained by the prevailing geological conditions, such as the great

quantities of water found in strata which have been undergoing exploitation for several decades. The reasons for the weak effects cannot be explained solely by geological conditions, however, since it is as yet unclear what role is played in the production of the effect by other factors such as bore diameter, thickness of the cement layer surrounding the column, position of the neutron source and radiometric apparatus with respect to the bore walls, the cement salt content, etc.

For this reason, the investigation of the above-mentioned problems is one of the basic tasks whose solution determines the correct interpretation of test results obtained by the NA of sodium method under the conditions of low mineral content for waters occurring under the petroleum layer.

POTENTIALITIES FOR THE INDUCED ACTIVITY METHOD FOR THE QUANTITATIVE ESTIMATE OF OIL SATURATION AND OTHER CHARACTERISTICS OF STRATA

-USSR-

[Following is the translation of an article by K.A. Kozanov in "Yadernaya Geofizika" (Nuclear Geophysics), Moscow, 1959, pages 103-109.]

Developments in nuclear physics are providing geologists with newer and newer methods of investigating borewell profiles and rock layer samples. One of the new radioactivity methods is the radiation analysis of rock samples (the induced activity method), which as a result of work done at the Petrology Institute of the USSR Academy of Sciences and the special-project teams of the Tatneftegeofizik trusts as well as other enterprises is already being employed in the petroleum industry for the classification of various rock structures according to water and petroleum content (1,2).

The use of this method for the solution of this particular problem is based on determining the radiation from the Na^{24} formed out of Na^{23} by neutron bombardment. In the water-bearing sandstones of the eastern regions, the Na content reaches 1% of the rock weight, but is 3-10 times smaller in the petroleum-bearing strata. For this reason, the water-bearing layers are characterized by heightened activation intensities as compared with the petroleum-bearing strata.

There can be no doubt than in the future this method will be even more widely used in the petroleum industry, as well as in mining geology especially both for qualitative and quantitative determination of the content of a specific element in rock samples.

In this connection, it would be of some interest to

discuss the future prospects for the application of induced radioactivity (NA -- navedennaya aktivnost') to the study of the chemical composition of rocks and the quantitative determination of useful mineral contents in rocks, first and foremost to determinations of the petroleum-content coefficients in cased bore wells.

The determination of the petroleum-content coefficient k_N with the aid of the NA method is done indirectly. It involves measuring the Na content in the stratum pores; then, knowing the NaCl concentration in the residual water, it is possible to determine the quantity of water per unit volume in the rock structure, and then knowing the porosity of the stratum, one determines the coefficient k_V of water content and the coefficient of petroleum content $k_N = 1 - k_V$.

The intensity of radiation emanating from the Na^{24} (J_{Na}) depends not only on the Na content in the stratum pores, but also on a number of other factors, of which the major ones are the following: a) strength of the neutron source; b) sensitivity of measuring apparatus; c) diameters of bore, casing column, and apparatus housing; d) presence of Na in the structure of the rock formation and cement surrounding the casing column.

The first two of these factors can be compensated for by proper equipment calibration, and the third one may be accounted for by setting up the function $J_{Na} = f(C_{Na})$ for each specific bore structure and housing diameter.

It is more difficult to account for the effect produced by the Na in the rock structure and cement lining. Because of this, the first attempts at a quantitative determination of k_N by the NA method by special-project team member from Tatneftegeofizika Ye.B. Blankov (1), and also at the Petrology Institute, were based on the assumption that Na^{24} was found only in the stratum water; it was also assumed that the stratum porosity, mineral content in the stratum water, and eccentricity of the column were the same for both the water-bearing and petroleum-bearing intervals. This made it possible to disregard the effects of all other factors, and to use the method of interpretation according to relative parameters.

In doing this, Ye.B. Blankov employed the formula (1)

$$k_N = 1 - \frac{(J_{Na})_N \Psi_V}{(J_{Na})_V \Psi_N}$$

where $(J_{Na})_N$ and $(J_{Na})_V$ are the Na^{24} radiation intensities in the petroleum-bearing and water-bearing intervals, respectively; ψ_N and ψ_V are the coefficients compensating for the differing densities of thermal neutrons in the petroleum- and water-bearing intervals which are exhibited as a result of their different chlorine content.

For the value of ψ_V/ψ_N, Ye.B. Blankov took the ratio of Al^{28} radiation intesities, as induced in the stratum and the cement lining, or the Mn^{56} radiation intensities as induced in the casing column measured against the water- and petroleum-bearing intervals.

In our determination of k_N, we took for our ψ_V/ψ_N value the ratio of thermal neutron mean-lives in the petroleum- (τ_N) and water-bearing (τ_V) strata, i.e.,

$$\frac{\psi_V}{\psi_N} = \frac{\tau_N}{\tau_V} = \frac{\sum_i N_i\sigma_i + N_N\sigma_N + (N_{Cl}\sigma_{Cl})_V}{\sum_i N_i\sigma_i + N_N\sigma_N + (N_{Cl}\sigma_{Cl})_N},$$

where $\sum_i N_i\sigma_i$ is the microscopic cross-section of neutron absorption by the rock structure; $N_N\sigma_N$ is the same as the above for the petroleum at a given porosity; $N_{Cl}\sigma_{Cl}$ is again the microscopic cross-section of neutron absorption for Cl at a given mineral content in the stratum water and a given water content coefficient.

The values of k_N for several bore-holes determined by this technique differed by 1.5-1.6 times from those obtained by the resistivity method.

As was indicated above, in determining k_N by the method described above, it was assumed that Na^{24} is induced only in the stratum water. However, this supposition cannot be deemed sufficiently acceptable, since the layer and the cement especially both contain a definite amount of Na which cannot be ignored. For example, according to data found in one of the references (5), Portland cement contains from 0.5 to 1.3% $Na_2O + K_2O$ by weight. It is obvious that such a considerable amount of Na and K [see Note] in the adjacent medium will have a large effect on the measurements in view of the low penetrability of the NA technique. [Note: Radiation from the K^{42} isotope, which has a half-life of 12.5 hours, is very difficult to distinguish from Na^{24} radiation by the methods used.]

In order to study this effect, an experiment was carried out on a 20% porosity sand layer containing 200 grams NaCl per 1 liter of pore liquid. The bore in the model layer had a diameter of 30 centimeters ($11\frac{3}{4}$") and was "cased" with a 6" column and cement lining. The assembled form was irradiated from a $2 \cdot 10^7$ neutron/second neutron source for 15 hours. After the completion of irradiation, measurements were taken of the time-dependent decline in radioactivity in the entire model along with the column and cement lining, as well as in the cement lining and column separately.

The derived dependence relationships between radiation intensity and time (see Figure) represent the composite curves of declining activity of Al^{28} ($T_{\frac{1}{2}}$ = 2,3 minutes), Cl^{38} ($T_{\frac{1}{2}}$ = 38,5 minutes), Ca^{49} ($T_{\frac{1}{2}}$ = 8,4 minutes), and mainly Mn^{56} ($T_{\frac{1}{2}}$ = 2,6 hours) which is activated in the column, as well as Na^{24} ($T_{\frac{1}{2}}$ = 15,1 hours).

The separation of the curves to determine the intensity of radiation for individual isotopes shows that the radiation from Na^{24} in the cement lining makes up about 60% of the total Na^{24}, i.e., the rock formation yields only about 40% of the measured Na^{24} radiation.

Even in the case of cements containing 2-3 times less Na than that used in the present experiment, the percentage of Na^{24} radiation from the cement lining of the given structure ($d_{bore} = 11\frac{3}{4}$", $d_{lining} = 6$") will constitute 30-45% of the measured radiation from the Na^{24}, and the effects at the water-petroleum contact will not exceed 150-250%.

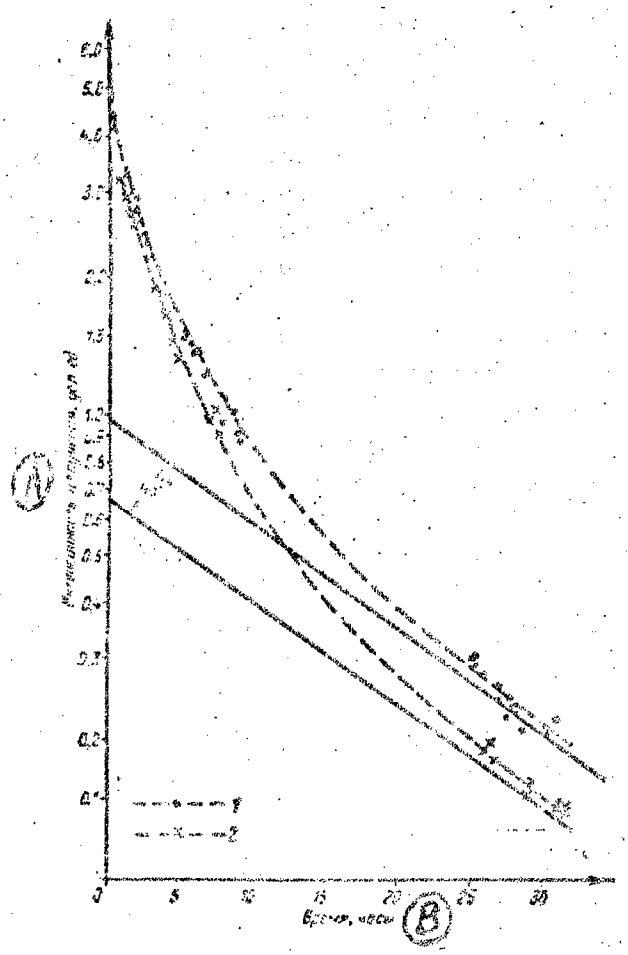
It is perfectly clear that such a strong and diversified effect (with various types of cement) of the neighboring zone must create considerable difficulties in determining the petroleum content coefficient.

There are two conceivable methods of eliminating the effect of Na contained in the cement:

1) The addition to the cement of a material with a high thermal neutron absorption cross-section which would absorb the major portion of the neutrons in the region of the cement lining, thus reducing Na activation in the cement. This, however, gives rise to a number of complications:

a) The material must be cheap, and its addition should not affect changes in the current methods of lining the bore with cement;

b) The presence of a high-absorption material in the



Radioactive Decay Curves for an Activated Model of a Water-Bearing Sand Layer

A = Radiation intensity, in representative units.
B = Time, in hours.
1 = Radiation from entire model;
2 = Radiation from cement lining and column.

---

cement lining will "suck off" neutrons from the stratum itself, thus reducing the Na activation in the latter to such an extent that radioactivity measurements would become difficult.

2) It is possible to determine the Na content in the cement by cavity measurements for example, and then to introduce a correction for the cement Na content into the measurement results. This requires a knowledge of the way in which J_{Na} depends upon the Na content in the cement and also on

bore and column diameters. This, of course, entails considerable errors, especially if the intensity of the measured sodium radiation emanating from the stratum is small compared to that of the cement radiation.

In addition to this, such a compensation for the Na content in cement is only possible in those cases where the Na content is equal when measured against the cavity and the stratum formation in which we are interested. The results of certain studies have cast doubt on whether this is the case, however.

Back in 1955, on the basis of a comparison of the effects at water-petroleum contacts obtained in bore wells and models constructed at the Petrology Institute (3), a hypothesis was expressed regarding the possibility of cement lining salination in areas adjacent to water-bearing strata. This may also account for the high effects observed in measurements taken at water-petroleum contact levels by the NA method (effects of up to 500-700%). These values are significantly in excess of the limit indicated above (150-250%) and obtained on the premise of equality between the cement radiation at both the water- and petroleum-bearing intervals. Such pronounced effects may partially be explained by the eccentric positioning of the column. The possibility cannot be overlooked, however, that another cause for this phenomenon lies in the sodium enrichment of the cement lining in the area adjacent to the water-bearing layer.

Unfortunately, no direct studies have as yet been carried out on the bores to investigate the presence, degree and mechanism of this phenomenon. It is important to study it, however, in order to make a quantitative interpretation not only of the NA method, but the NGM (neutron-gamma method) and NNM (neutron-neutron method) according to thermal neutrons as well.

If the hypothesis relating to the salination of the cement lining should fail to be confirmed, then it will be possible to employ the NA method with a low-energy neutron source (Sb + Be, for example). This lowers the penetrability of the method, and the results will depend largely on the Na content in the cement. The measurements which result from the NA method when Po + Be and Sb + Be sources are used will depend differently on the Na content in the cement. Making combined use of these two measurements, it may be possible to determine two unknown quantities -- the Na contents in the stratum and cement. It is perfectly obvious that due to

measurement errors, the employment of such a procedure will be possible only in those cases where the effect of sodium in the stratum on the measurements using Po + Be sources constitutes not less than several tenths of the total registration of radiation intensity.

Thus, the problem of determining Na in the stratum under the conditions of a cased bore-hole by the NA method entails considerable difficulties due to the effect of the sodium in the cement lining. The study of this problem will require a number of complex tests on bore-holes, including the selection of samples from the cement lining surrounding the casing tube; but the above-mentioned problem is of such importance, however, that the completion of these experimental tests is, in our opinion, absolutely necessary to finding out in the near future the extent of the theoretical possibilities of using the existing NA techniques for its solution.

In addition to testing the existing NA techniques using Po + Be sources, it will be necessary in the future to inquire into the possibilities of employing powerful high-energy neutron sources, such as neutron generators. This will aid in raising the penetrability of the NA method as well as other neutron techniques.

Completely different is the situation as regards those mining bore-holes where there is no casing and other factors which complicate the procedure, such as the effects of Na in the cement on measurements of the petroleum content. For this reason, it is possible in such cases to make a fairly precise determination of the content of a number of elements. The method of induced radioactivity could be used successfully for determining the percentage content in the rock sample of such elements having a high activation cross-section as Mn, V, Al, Cu, Au, Ag, etc. The solution to this problem permits the use of the same apparatus as is employed in other radioactive bore-hole study methods. In an undertaking of this sort it is necessary to establish through the use of models the dependence of the measured radiation intensity for the given isotope on its percentage content in the rock sample, its density, and moisture content for bore-holes of various diameters. Finally, it is necessary to note that in determining the content of elements with very high activation cross-sections, it is possible to obtain not only point-by-point measurements, but also a continual curve registration.

The induced radioactivity method has every prospect of coming into wide use for the study of the chemical composition of rock structures in bore-holes and especially in sample form. The work done at the Petrology Institute has shown that the use of polonium-beryllium sources having a power of 5-10 Curies of polonium makes it possible to determine the vanadium content in samples having as little as 0.1% of this element, and also the indium content in samples which contain 0.01% or more (3).

In sedimentary rocks, considerable interest is posed by the determination of aluminum content, since this permits an estimate to be made of one of the important characteristics of the substances -- its clay content. Al^{28} has a rather large activation cross-section, and the determination of the aluminum content in rock samples presents no difficulty in view of the usual concentrations of this element. The determination of the aluminum content under bore-hole conditions, however, requires that certain complicating factors be taken into account, such as the presence of aluminum in the clayey solution and clay crust adjacent to the permeable rock structures, the presence of cavities against some of the layers, etc.

Up until recently, the possibilities for using the NA method in studying the chemical composition of rocks had been limited by the low power of the Po + Be sources and the concomitant impossibility of significantly activating isotopes with smaller activation cross-sections. At the present time, powerful neutron sources (neutron generators and multipliers) for bore-hole measurements are in the process of being designed, while nuclear reactors are already available for the activation of rock samples by means of strong neutron beams. The use of such powerful neutron sources and high resolving-power spectrometers will make it possible to separate out the γ-radiation of isotopes having small activation cross-sections. In studying samples, furthermore, it is possible to register both the γ- and β-radiation. All this will make it possible to make rapid and sufficiently thorough studies of the chemical composition of rocks.

Bibliography

1. Blankov, Ye.B., Blankova, T.N., Blyumentsev, A.M., Guberman, Sheh.A., "The Effectiveness of Various Methods of Classifying Devonian Sandstone Formations According

to Water- and Petroleum-Content in the Tatar Oil Fields". Tekhn. byull. ob"yedineniya Tatneft' "Tatarskaya neft' " (Technical Bulletin of the Tatneft' "Tatar Oil" Joint Enterprises), No 4-5, 1956.

2. Kukharenko, N.K., Shimelevich, Yu.S., Bespalov, D.F., Odinokov, V.P., "A New Geophysical Method of Discovering Petroleum and Water-Bearing Strata and Determining Water-Petroleum Contact in Cased Bore-Wells", Neftyanoye khozyaystvo (Petroleum Industry), No 3, 1956.
3. Kukharenko, N.K., Serdiy, A.G., Odinokov, V.P., "Demarcation of Water- and Petroleum-Bearing Strata and Determination of the State of Water-Petroleum Contact Under the Conditions of Cased Bore-Wells by the Neutron Beta-Gamma Method With Scintillation Counter and the Neutron Beta Method", In a collection of papers entitled "The Use of Radioactive Isotopes in Petroleum Industry Studies", Gostoptekhizdat, 1957.
4. Leypunskaya, D.N., Gauer, Z.Ye., "Neutron Activization Analysis of Rock Samples", Byull. Nauchn.-tekhn. informatsii (Bulletin of Technical-Scientific Information) of the USSR Ministry of Geology and Mining Conservation, No 1, (3), 1956.
5. Toropov, N.A., "Cement Chemistry", Promstroyizdat, Moscow, 1956.

THE EFFECTIVENESS OF METHODS OF INDUCED ACTIVITY OF SODIUM AND CHLORINE IN THE SEPARATION OF DEVONIAN SANDSTONE ACCORDING TO OIL CONTENT

-USSR-

[Following is the translation of an article by T.N. Blankova in "Yadernaya Geofizika" (Nuclear Geophysics), Moscow, 1959, pages 110-120.]

The experimental-methodological team of the Tatneftegeofizika has been working since 1955 on improving the induced activity of sodium (NA Na -- navedennaya aktivnost' Na) method, suggested in 1954 by the USSR Academy of Sciences Petrology Institute for the classification of rock structures according to water and petroleum content (2).

Since 1957, the team has been directing its efforts toward the development of an induced activity method for chlorine (NA Cl), to be used for the same purpose, but requiring much smaller time expenditures than the NA of sodium method.

Over the period that this work has been going on, the NA Na method was employed in studying 38 bore-holes (13 of which were perforated). The NA Cl method has been used on 18 bores (with a total of 165 NA logs taken).

An important result of the efforts to develop and perfect the NA Na and Cl methods was their introduction into industry in 1958 (largely at the Bavlinskiy fields of the Tatar Republic).

The integration of the NA Na and Cl methods into actual use was greatly assisted by the compilation and transmission to the Tatneftegeofizik trust enterprises of instructions on the application of the techniques, which included directions on obtaining, processing, and interpreting NA data, as well as on making cost estimates for

water-petroleum contact (VNK — vodo-neftyanoy kontakt) tests by the NA Na and Cl methods.

Of great importance in the effort to introduce NA Na and Cl methods into industry was the creation within the framework of the Bugul'minskaya Industrial and Geophysical expedition of a specialized radiometric team assigned to conduct studies on VNK by the NGK (neytronnyy gamma-kat-odnyy — neutron gamma-beta) and NA methods; an important role was also played by the maintenance of continuous contact with the geological service of the Bavlyneft' NPU (Neftе-Promyshlennaya Ustanovka — Petroleum Industry Facility).

Positive results with the NA Na and Cl techniques were obtained as early as the first year of industrial use at the Bavlinskiy fields.

All the work performed by these methods at the Bavlinskiy fields gave consistent results as to the character of the liquid content in the sandstone formations at the intervals studied; these were used by the field workers for judiciously choosing the perforation interval. This was of especially great importance in working with perforated bore-holes, where the problem of determining the location of the water-petroleum contact level cannot, in many cases, be solved by other means.

A generalization of the considerable body of material obtained in the industrial application of the NA Na and Cl methods made possible the further improvement of techniques, and also allowed the establishment of more precise criteria as to the water- and petroleum-bearing state of the sandstone formations according to NA Na and Cl tests, as well as to determine the effectiveness of these methods as a tool in classifying Devonian sandstones according to water and petroleum content.

1. Water and Petroleum Content Criteria for Devonian Sandstones According to the NA Na and Cl Techniques

As a result of an analysis of the materials obtained from bore-hole studies by the NA Na and Cl methods, it is now possible to present water and petroleum content criteria for sandstone formations according to NA data. It would seem that the most appropriate criterion is the magnitude of absolute intensity values for the γ-radiation

from the Na and Cl obtained by reducing the NA curves into their component J_{Na} and J_{Cl} values (see the article by Ye. B. Blankov in the present collection).

As experience has shown, however, these values are not sufficiently maintained in repeated bore-hole measurements, due to the difficulty of creating absolutely identical conditions for each measurement; methods for calibrating the NA apparatus, furthermore, have not as yet been developed.

As a result of this, it was decided that the criterion for water and petroleum content in the rock formation should be quantity

$$\beta_{Na} = \frac{J_{oNa}}{J_{oNa} + J_{oMn}} \quad \text{or} \quad \beta_{Cl} = \frac{J_{oCl}}{J_{oCl} + J_{oMn}} \quad [\text{see Note \#1}]$$

which gives the proportion of the indicator-element (Na or Cl) radiation in the total radiation recorded in the NA measurements [see Note #2]. [Note #1: J_{oCl}, J_{oNa}, J_{oMn} are the radiation intensities corrected for infinite irradiation time]. [Note #2: We neglect the Al^{28} radiation which is in evidence only during the first minutes of measurement. In addition to this, in determining β_{Na} it is possible to neglect the Cl^{38} radiation, and in determining β_{Cl}, to neglect the Na^{24} radiation (this is permitted in dealing with the practical problem of locating the VNK level)].

The choice of a relative quantity to serve as a criterion permits the circumvention of NA data calibration and partially eliminates various factors involved in obtaining these data.

Taking into account the fact that $J_{oCl} \ll J_{oMn}$ (maximum value of $\frac{J_{oCl}}{J_{oMn}} = 0{,}15$), it is possible to take

$$\beta_{Cl} = \frac{J_{oCl}}{J_{oMn}}.$$

This was the actual criterion used in interpreting NA Cl data.

In establishing the variation interval of β_{Na} and β_{Cl} for water- and petroleum-bearing sandstones,

as well as sandstone in the intermediate zone, the values for β_{Na} and β_{Cl} obtained for points opposite the strata being studied were compared with the strata logs obtained by the electrical resistivity technique.

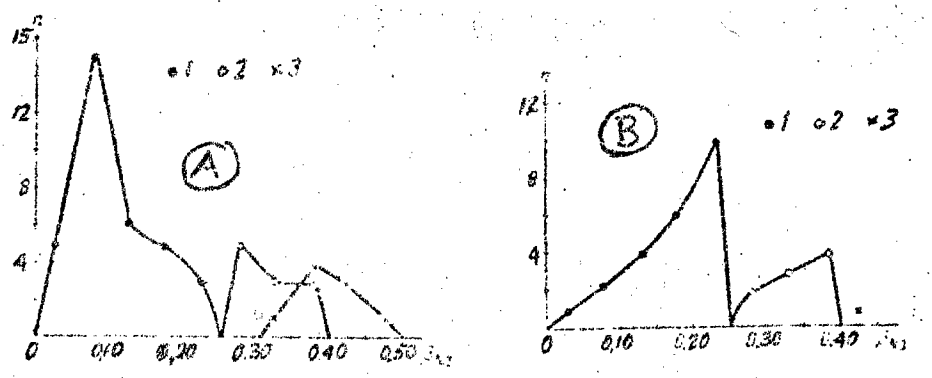


Figure 1. Resolving Power of the NA Na Method in Classifying Formations According to Water and Petroleum Content

A = Unperforated bore-holes.
B = Perforated bore-holes.
1 = Petroleum-bearing sandstone.
2 = Intermediate zone.
3 = Water-bearing sandstone.

For purposes of analysis, materials used included data both on perforated and unperforated bore-holes. In bore-holes where the situation as regards water-petroleum contact changed in comparison with data obtained by the resistivity method, only those strata whose logs were undoubtedly correct were taken into account.

The tests were performed only on those bore-holes for which a sufficient length of time had elapsed since the pouring of the cement lining, due to the fact that the values for β_{Na} and β_{Cl} turn out to be inordinately low in freshly-bored shafts because of the penetration of boring fluid filtrate into the adjacent strata.

All of the analyzed values for β_{Na} and β_{Cl} were ob-

tained by NA procedure using a standard NGK-6S apparatus with MS-9 counters.

Figures 1 and 2 show the distribution of Devonian sandstones with different saturation fluid according to the β_{Na} and β_{Cl} values (the n on the graphs stands for the number of points at which corresponding β-readings were obtained.

Data from 26 bore-holes were used in constructing Figure 1; it turned out to be possible in this case to give the distributions for both perforated and unperforated bores. Figure 2 was constructed on the basis of measurements from a total of 17 perforated and unperforated bore-holes included in the general distribution.

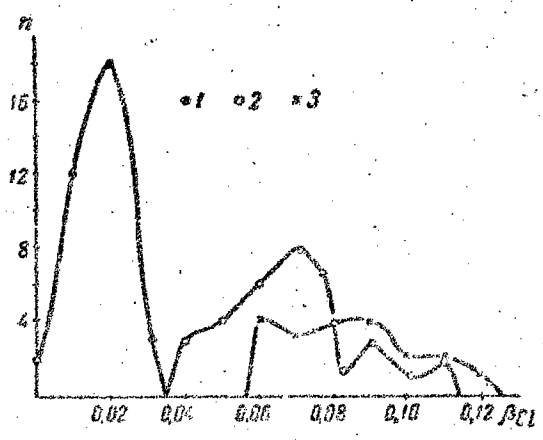


Figure 2. Resolving Power of the NA Cl Method in Classifying Formations According to Water and Petroleum Content

1 = Petroleum-bearing sandstone.
2 = Intermediate zone.
3 = Water-bearing sandstone.

An examination of Figures 1 and 2 indicates the following limits to the variation of β_{Na} and β_{Cl} values for

sandstones with differing fluid content (mineral content of stratum waters = 260-300 grams/liter):

Table 1

Portion of indicator-element radiation in total radiation registered by NA method	Petroleum-bearing sandstones	Intermediate zone and water containing sandstones	Water-bearing sandstones
β_{Na}	0-0,24	0,25-0,40	0,35-0,45
β_{Cl}	0-0,03	0,04-0,11	0,06-0,12

The limits for β_{Na} indicated above are the same for both the perforated and unperforated bore-holes. The most probable value for β_{Na} in petroleum-bearing sandstones is somewhat higher for perforated bore-holes ($\beta_{Na\ prob.} = 0,15$) than for the unperforated ones ($\beta_{Na\ prob.} < 0,1$). This can very probably be explained by the penetration of salt water into the petroleum-bearing stratum in the perforation interval.

For water-bearing sandstones, the limits of variation for β_{Na} have been established only for the unperforated bore-holes, since in perforated bores NA Na measurements were, as a rule, not carried out against known water-bearing strata.

It is necessary to note, however, that insofar as the water-bearing portion of a layer is not perforated and does not come in direct contact with the perforation interval, its properties in perforated bore-holes must remain approximately the same as in unperforated bore-holes. For this reason, it is possible to assume that the limits of variation for β_{Na} in perforated bores are the same as in the unperforated ones.

Since the smaller body of data obtained from studies

by the NA Cl method did not allow the construction of separate β_{Cl} distributions according to perforated and unperforated bore-holes, it is impossible to draw any conclusions as regards any differences in β_{Cl} values for the two types of bores.

The limits of β_{Na} and β_{Cl} variation for strata of differing fluid content examined above are being used by the enterprises of the Tatneftegeofizik trust in interpreting NA data.

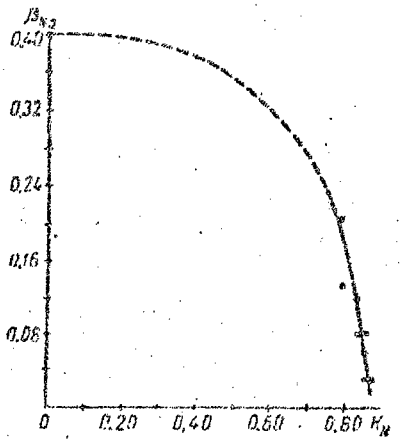


Figure 3. The Connection Between β_{Na} and k_N

As is shown in Table 1, the values for β_{Na} measured against petroleum-bearing sandstones vary within fairly wide limits (0-0,24). Such an interval of β_{Na} values cannot be ascribed to measurement errors.

An attempt was made to establish the correlation between the values for β_{Na} measured against petroleum-bearing layers in unperforated bore-holes and the petroleum content coefficient k_N, determined for these layers with the aid of electrometric data.

Since for this or that reason (heterogeneity of stratum, lack of certain data necessary for determining k_N, etc.) it was impossible to determine the value of k_N for every bore-hole for which NA measurements were available, the body of data used for this particular study was not extensive.

Even this meager data, however, indicates the presence of a single-valued relationship between β_{Na} and k_N, accord-

ing to electrical resistivity measurements (see Figure 3).

It turned out to be possible to construct a single-valued plot of the curve corresponding to the variation of k_N from 0.78 to 0.88, which illustrates the presence of a close correlation between β_{Na} and k_N (corresponding interval for values of β_{Na} = 0.03 ÷ 0.20).

The portion of the curve for values of $k_N < 0.78$ was constructed conditionally. For the case $k_N = 0$, the most probable value for β_{Na} in water-bearing layers was chosen.

The general configuration of the curve in Figure 3 corresponds to the prevailing concepts on the character of the dependence of values obtained by the radiometric method on the water content of the structural trap.

k_N as determined by electrometric data does not correspond to the actual petroleum content in the structural trap and is in sufficient error to make the curve merely an illustration which cannot be presently used for practical purposes.

It is necessary to point out that the establishment of a correlation between β_{Cl} and k_N for petroleum-bearing strata is impossible with present techniques and measurement methods, since the β_{Cl} values measured against these strata do not exceed the boundary limits (see the article by Ye.B. Blankov in the present volume).

2. Resolving Power of the NA Na and Cl Methods

An analysis of the materials obtained by means of the NA Na and Cl methods permits us to make some preliminary conclusions as to the effectiveness of these techniques in classifying Devonian sandstones according to water and petroleum content, and to compare it with the effectiveness of the NGM (neutron gamma-method) in solving the same problem.

Quantitatively, the effectiveness of the NA and NGM methods in classifying water- and petroleum-bearing rocks can be characterized by introducing the concept of the resolving power for each method, defined as the ratio of the difference between the most probable β_{Na} and β_{Cl} values or the relative NGM anomaly, $\frac{J_{stratum}}{J_{cavity}}$ for water- and petro-

leum-bearing strata, to the sum of the half-widths of the distributions for these strata. The half-width of the distribution is here defined as the difference between the most probable values for β or $\frac{J_{stratum}}{J_{cavity}}$ and the values for these quantities above which for the petroleum-bearing strata and below which for the water-bearing strata lie not more than 10% of the points (or levels).

With such a definition of the resolving power, a reliable separation of water- and petroleum-bearing strata is characterized by a resolving power greater than 1; with a resolving power less than 1, a reliable separation of petroleum- and water-bearing strata is impossible.

Below we have Table 2, representing a comparison between the resolving powers of the of the NA technique and the NGM. The resolving power of NA was in this instance deter-

Table 2

Strata separated	Resolving power		
	NGM	NA Na	NA Cl
Unperforated Bore-Holes			
Petroleum- and water-bearing...	0.9	1.5	2
Petroleum-bearing -- intermediate zone + water-bearing....	0.7	1.1	---
Intermediate zone -- water-bearing.....	---	0.5	0.2
Perforated Bore-Holes			
Petroleum- and water-bearing...	0.4	---	---
Petroleum-bearing -- intermediate zone + water-bearing....	---	1.1	---

mined by means of the distributions shown in Figures 1 and 2. Data on the resolving power of the NGM were taken from the materials obtained by V.I. Gorbunova through an analysis of the distributions of sandstone strata of varying fluid content according to the values of $\frac{J_{stratum}}{J_{cavity}}$ (Figure 4) as presented in the report for July 1958 of the research team

of the Tatneftegeofizik trust.

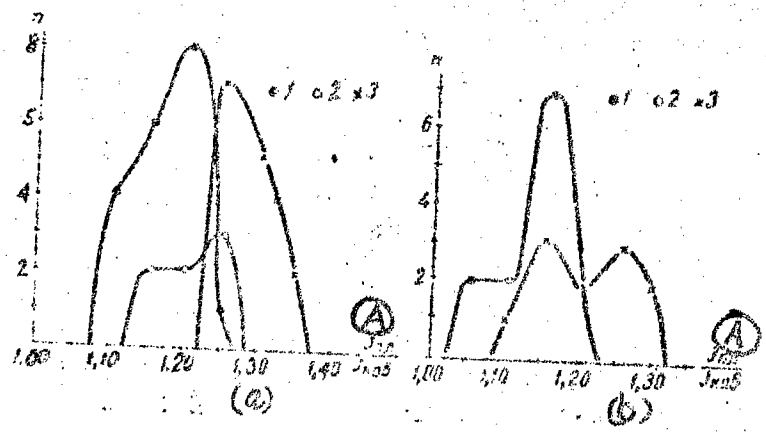


Figure 4. Resolving Power of the NGM Method.
(a) = Unperforated bore-holes.
(b) = Perforated bore-holes.
A = $\frac{J_{stratum}}{J_{cavity}}$
1 = Petroleum-bearing sandstone.
2 = Intermediate zone.
3 = Water-bearing sandstone.

It is necessary to note that in the case of the perforated bore-holes, the lack of NA Na measurements against water-bearing strata did not allow a determination of the resolving power for the separation of water- and petroleum-bearing layers. Because of this, in order to compare the effectiveness of the NA and NGM methods in perforated bore-holes, the resolving power for the separation of petroleum-bearing strata from the combination of water-bearing and moist (or intermediate) zones was used as given in Table 2.

It follows from Table 2 that the resolving power of NA Na and Cl in separating petroleum-bearing strata from water-bearing layers or from a combination of water-bearing and intermediate zone sandstones is greater than 1 both for perforated and unperforated bore-holes.

This corresponds to the fact that the distributions for petroleum- and water-bearing strata, and even for petroleum-bearing layers and intermediate zones do not overlap on Figures 1 and 2, and testifies to the reliable separation of petroleum-bearing layers by the NA Na and Cl methods

both for perforated and unperforated bore-holes.

As regards the resolving power of the NA Na and Cl methods in separating intermediate zone sandstones or moisture-laden sandstones with residual petroleum from water-bearing sandstones, it is considerably less than 1. The corresponding distributions for β_{Na} and β_{Cl} overlap significantly. The NA Na and Cl methods do not permit an effective separation of water-bearing sandstones from intermediate zones or moisture-laden sandstones.

The resolving power of the NGM in separating petroleum- and water-bearing sandstones for unperforated bore-holes is close to 1 (the NGM method assures a satisfactory separation of petroleum- and water-bearing strata in such bore-holes); however, it turns out to be less than the resolving power of the NA Na and Cl techniques.

In perforated bore-holes, the resolving power of the NGM is considerably less than 1, which testifies to the extremely low effectiveness of the NGM in logging such bore-holes.

In examining the problem of the effectiveness of NA methods for estimating the water and petroleum content in perforated bore-holes, it is necessary to take into account several peculiarities involved in working with such bore-holes.

In particular, it is necessary to allow for the effect of salty or fresh water penetration into the stratum being studied through the perforation interval.

The first phenomenon occurs in gusher wells quenched with salt water before pumping, as well as in bore-holes with gushing stopped by water in-flow; the second occurs after the bore is washed out with fresh water.

Salt-water penetration into the petroleum-bearing layer in many cases does not prevent a correct estimate of the fluid content in the stratum by the NA method. Thus, even though the distributions shown on Figures 1 and 2 were constructed on the basis of data obtained from both gushing and water-drenched bore-holes, as well as from bores tapped by the pumping method, overlapping of the limits of β variation for petroleum- and water-bearing layers does not occur as a result of this.

The penetration of fresh water into a stratum saturated with mineral-containing water, as has been shown experimentally, has a stronger influence on NA results: the β_{Na} and β_{Cl} values may be too low, thus giving rise to errors

in interpretation.

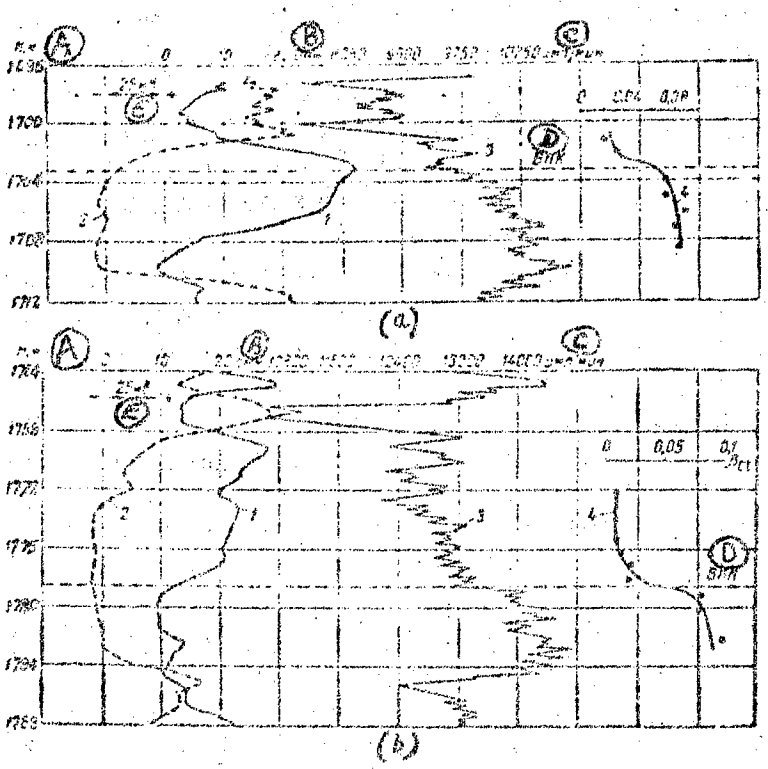


Figure 5. VNK Determination by the NA Cl Method.
A = Depth, in meters.
B = Ohm-meter-millimotor^2 (volume resistivity units).
C = Amperes/minute.
D = Water-petroleum contact (VNK).
E = Millivolts.
(a) = Bore-hole No 737 of the Pavlovskaya sector (perforated).
(b) = Bore-hole No 876 of the Pavlovskaya sector (control).
1 = Calibration resistivity log.
2 = S.P. (Self-Potential) log.
3 = NGM log.
4 = Plot of β_{Cl} variation with depth.

The differing effect on NA results produced by the penetration of fresh water into a stratum saturated with mineral-containing water is obviously determined by the difference in the water penetrability of the petroleum- and water-bearing layers.

The effect produced by the penetration of fresh water into the stratum can be eliminated by bailing-out operations prior to making the NA studies.

What was said above concerning the reliable separation of water- and petroleum-bearing layers by the NA Cl method can be illustrated by the plots of β_{Cl} variation with depth within the limits of the stratum being studied, as shown in Figure 5 for two bore-holes, one of which is the control bore (unperforated) and the other is perforated. Both plots permit a sufficiently reliable determination of the location of the water-petroleum contact level as the lower boundary of the petroleum-bearing stratum, which corresponds to the position of the VNK that is well determined in the given cases by means of the NGM log (Figure 6).

It is necessary to point out that the determination of the water-petroleum contact level by means of NA Cl data obtained from Bore-Hole No 787 was not hindered by the fact that it had been quenched by salt water prior to the initiation of measurement operations.

3. A Comparison of Results Obtained by the NA Na and Cl Methods With Industrial Data

One of the most significant criteria for the effectiveness of this or that method for the separation of rock structures according to water or petroleum content is the confirmation of conclusions drawn from data obtained from it by the results of actual bore trials.

We have at our disposal the results of trials on 11 bore-wells which had been studied by the NA method.

In eight of these, the trial results fully confirmed the conclusions based on NA measurements. Furthermore, four wells out of these eight yielded water-free petroleum, as was expected on the basis of NA data, one yielded fresh water, and the rest turned out to be infiltrated with salt water.

Three wells with strata characterized as petroleum-bearing by means of NA, yielded petroleum mixed with water. Yet there is no basis for assuming that in these cases the NA method gave incorrect results, inasfar as the trial results depend not only on the fluid filling the layer in the perforation interval, but also on the quality of underlying water insulation, vertical permeability of the stratum, etc.

In particular, of the three bore-wells in which the trial results did not confirm the conclusions based on NA, one has a perforation interval adjacent to the water-bearing stratum boundary, another has anomalous water infiltration along permeable interstratifications (with the top and bottom of the stratum infiltrated) which complicates insulation, and the third bore had a certain percentage of water from the very start of its exploitation despite the great distance from the perforation interval to the VNK; this, apparently, has to do with poor cementing.

The extent of tests so far is wholly inadequate for making a final evaluation of the effectiveness of NA in perforated bore-holes.

Even at this point, however, it is already clear that the NA method is practically applicable for determining the VNK level in unperforated bores.

Another important confirmation of the geological effectiveness of the NA method and the objectivity of the information obtained through it may be had by comparing the work done by the NA method with data from chemical analysis of waters occuring under the petroleum layer.

According to chemical analysis data, the ratio of the numbers of chlorine and sodium ions $\frac{Na^+}{Cl^-}$ in the stratum waters of the Devonian formations in the southeastern part of the Tatar Republic fluctuates from 0.63 to 0.67 (1).

According to NA Na and Cl data, the activity ratio $\frac{J_{oCl}}{J_{oNa}}$ varies for water-bearing strata within the interval from 0.13 to 0.15, which values, taking into account the relationship of effective cross-sections, percentage of activated isotopes in the natural mixture, emanation of γ-quanta, etc. yield as estimates for the ratio of sodium and chlorine atoms values from 0.6 to 0.7. This is sufficiently close to the results obtained with the aid of chemical analysis.

Bibliography

1. Kazmina, T.I., "Geochemical Conditions of the Formation of Devonian and Earlier Deposits in the Volga-Ural'skaya Oblast' ", In the collection "On the Conditions of Petroleum Formation", edited by Z.L. Maymin, Gostoptekhizdat,

1955.

2. Shimelevich, Yu.Z., "Activation Analysis of Mining Rock Structures Within the Bore-Hole and Its Use in Determining the Location of Petroleum- and Water-Bearing Layers" Dissertation Fund of the Petrology Institute of the USSR Academy of Sciences, 1957.

METHOD OF DISTINGUISHING BETWEEN WATER AND OIL SATURATED STRATA BASED ON THE APPLICATION OF A PULSED NEUTRON SOURCE

-USSR-

[Following is the translation of an article by V.G. Yerozolimskiy and A.S. Shkol'nikov in "Yadernaya Geofizika" (Nuclear Geophysics), Moscow, 1959, pages 337-346.]

Introduction

The neutron method of petroleum bore-well logging, being used extensively in the Soviet Union, as is known, permits one to determine the location of hydrogen-filled (porous) layers. In order to judge as to the productiveness of a given stratum, however, it is necessary to know what sort of fluid is found in the porous spaces of the rock structure, i.e., whether these spaces contain water or petroleum. In a number of cases this can be done by comparing logs obtained by the neutron and electrometric methods. As a rule, a more or less clear interpretation can be had only for sandstones; with limestone or dolomite strata such a comparison is practically impossible. It should also be pointed out that, as is known, it is impossible to take electrometric measurements for cased bore-holes; for this reason, the method cannot be used to follow changes in the levels of the strata-filling fluid during exploitation.

Many attempts have been made over the last few years to develop the method of determining the location of the water-petroleum contact level in cased bore-holes with the aid of radioactivity techniques. Up to the present time, there has been significant progress in this direction (3,7) although the problem as a whole has not as yet been solved. Success has been achieved in making satisfactory demarcations

of the water-petroleum contact level within the limits of a homogeneous stratum in cases where the water occurring under the petroleum layer has a high mineral content. The technique makes use of sodium chloride present in the mineral-containing water and absent from the petroleum. The presence of chlorine in the water leads to higher readings against the water-containing portions of the stratum as against those for the petroleum bearing layers on the neutron-gamma log. The opposite is observed to hold for the neutron-neutron method logs.

Laboratory and industrial studies have shown that even in cases of high-mineral content in the water (200 grams/liter), however, the differences in the deviations of neutron-gamma and neutron-neutron method logs against the water- and petroleum-bearing portions of the stratum do not exceed 20-30% in a cased bore-hole (1). The effect can be increased to 50% by means of a scintillation counter (7).

Significantly greater effects can be had only by the method of measuring the induced radioactivity of sodium, which is one of the salts dissolved in the stratum waters, by means of a γ-spectrometer (8). With such a technique, and with water having a mineral content of 200 grams/liter, the meter indications for points in the region of water-petroleum contact differ by several times. This method, however, requires an irradiation cycle lasting several hours and measurements at each point; this makes it highly inconvenient under industrial conditions.

One drawback common to all of the above-mentioned methods of determining the location of the water-petroleum contact level is their insignificant "penetrability". The results of the measurements are significantly affected by bore parameters (dimensions, thickness of cement lining, salt content in cement, presence of boring fluid, etc.) (6). In addition to this, in many cases the flushing solution will penetrate into the porous parts of the stratum, and water saturation cones are often formed under exploitation. All this limits the practical possibilities of the above-mentioned methods.

From what has been said, it is possible to draw the conclusion that the problem of working out effective methods for determining the nature of the fluid in the stratum pores remains timely. New methods must permit the determination of productive strata and the location of the water-petroleum

contact level with both high and low mineral content in the waters occurring below the petroleum layer. It is necessary, likewise to broach the problem of quantitative petroleum content determination.

The Pulsed Neutron Source and the Theory Underlying Pulsed Measuring Apparatus

A method based on the measurement of the parameters of a non-stationary thermal neutron field using a pulsed neutron source (4,7) seems to hold high promise for the solution of a number of problems listed above.

Efforts have been initiated just recently at the Petrology Institute of the USSR Academy of Sciences toward the development of a small bore-hole neutron generator functioning in a pulsed range [see Note]. Without examining in the present article the design of such a generator, let us look into the theoretical background of pulsed measurement systems in general. [Note: A description of a small neutron tube for the bore-hole generator is given in the article by B.G. Yerozolimskiy, L.N. Bondarenko, et al., entitled "A Miniature Sealed Neutron Tube" found in the present volume].

Such systems consist of a pulsed neutron generator, recording apparatus, and control circuits. The recording device can be any type of thermal neutron indicator: a proportional counter filled with BF_3; a photomultiplier with a boron compound coated scintillator, or a Geiger counter registering the γ-rays emitted in the absorption of the thermal neutrons by the rock.

The neutron generator and the recording system are regulated by a special circuit in such a way that neutrons are emitted during a period T_1 and recorded over an interval T_3 which starts after waiting period T_2. Such measurement cycles follow one another many times each second, and the recording apparatus thus accumulates information about the intensity of the thermal neutron stream n in the location of the indicator over a time interval T_2 following the end of the radiation period T_1. Varying the length of T_2, it is possible to obtain the time-dependent function for the density of thermal neutrons in the rock.

Theoretical Estimates of the Possibilities of the Pulsed Neutron Method

Let us examine the possibilities of the method just described by means of an approximate theoretical analysis of the processes involved.

If we designate by $n(\vec{r},t)$ the neutron density at a point with radius-vector $\vec{r}$ after a time t following the emission of neutrons, then the differential equation describing the distribution of scattering thermal neutrons has the form (see reference source 2):

$$\frac{\partial n}{\partial t} = D\Delta n + q - \frac{n}{\tau} \qquad (1)$$

where D is the neutron diffusion coefficient; Δ is the Laplace operator; q is the number of neutrons arising in the medium per 1 centimeter^3/second; and τ is the mean life of the neutrons in the medium.

Since the pulsed source emits neutrons during a relatively brief time interval ($T_1 \ll T_2$), and practically all the fast neutrons decelerate over the same time period t_3, it may be assumed that the function of the distribution of the q sources differs from zero only during a small time interval equal to T_1 in duration. After a time $T_1 + t_3$ function $q = 0$, and equation (1) takes on the form

$$\frac{\partial n}{\partial t} = D\Delta n - \frac{n}{\tau}. \qquad (2)$$

The solution to this equation for a homogeneous medium appears in the form:

$$n(r,t) = \frac{1}{(4\pi Dt)^{3/2}} e^{-\frac{t}{\tau}} \int_V n(\vec{r}',0)\, e^{-\frac{(\vec{r}-\vec{r}')^2}{4Dt}} d\vec{r}' \qquad (3)$$

where $n(\vec{r}',0)$ is the initial distribution of thermal neutrons in the medium, proportional in our case to the function q.

In spherical coordinates formula (3) can be written in the form

$$n(r,t) = \frac{2}{r\sqrt{4\pi Dt}} e^{-\frac{t}{\tau}} e^{-\frac{r^2}{4Dt}} \int_0^\infty r'dr' n(r',0) e^{-\frac{r'^2}{4Dt}} \sinh\left(\frac{rr'}{2Dt}\right). \qquad (4)$$

Taking into account the fact that for a point source of thermal neutrons located at the origin of the coordinates and emitting Q neutrons per pulse, $\int_V n(r;0)dr' = Q$, we now have from (3) that

$$n(r,t) = \frac{Q}{(4\pi Dt)^{3/2}} e^{-\frac{t}{\tau} - \frac{r^2}{4Dt}}. \qquad (5)$$

Taking the first derivative of the expression (5) and setting it equal to zero, we determine the time of arrival of the thermal neutron wave maximum at the point r:

$$t_{max} = \frac{3}{4}\tau\left(\sqrt{1 + \tfrac{4}{3}\frac{r^2}{D\tau}} - 1\right). \qquad (6)$$

For a fast neutron point pulse souce, the initial distribution of thermal neutrons has a sufficiently good correspondence to the distribution of supertherma neutrons (5) and can be represented in the following way (initial energy of the fast neutrons is ~5 Mev (million electron volts) and $r > L_j$, where L_j is the deceleration parameter):

a) for hydrogen-free media (see reference 5)

$$n(r';0) = \frac{Q}{16\sqrt{2}\,\pi^{3/2} L_j^3} e^{-\frac{r'^2}{8L_j^2}}; \qquad (7)$$

b) for water (see reference 2)

$$n(r';0) = \frac{Q}{4\pi L_j^2 r'} e^{-\frac{r'}{L_j}}; \qquad (8)$$

c) for hydrogen-containing media (see reference 5)

$$n(r';0) = \frac{Q}{8\pi L_j^3} e^{-\frac{r'}{L_j}}. \qquad (9)$$

Substituting these formulae into expression (4), we obtain, respectively:

a) $$n(r,t) = \frac{Q}{[4\pi(Dt + 2L_j^2)]^{3/2}} e^{-\frac{t}{\tau} - \frac{r^2}{4(Dt+2L_j^2)}}; \qquad (10)$$

b) $$n(\tau,t)=\frac{Q}{8\pi\tau L_j^3}e^{-\frac{t}{\tau}+\frac{Dt}{L_j^2}}\left\{e^{-\frac{\tau}{L_j}}\left[1-\operatorname{erf}\left(\frac{\sqrt{Dt}}{L_j}-\frac{\tau}{2\sqrt{Dt}}\right)\right]-\right.$$

$$\left.-e^{\frac{\tau}{L_j}}\left[1-\operatorname{erf}\left(\frac{\sqrt{Dt}}{L_j}+\frac{\tau}{2\sqrt{Dt}}\right)\right]\right\}; \quad (11)$$

c) $$n(\tau,t)=\frac{Q\,Dt}{8\pi\tau L_j^3}e^{-\frac{t}{\tau}+\frac{Dt}{L_j^2}}\left\{e^{\frac{\tau}{L_j}}\left(\frac{1}{L_j}+\frac{\tau}{2Dt}\right)\times\right.$$

$$\times\left[1-\operatorname{erf}\left(\frac{\sqrt{Dt}}{L_j}+\frac{\tau}{2\sqrt{Dt}}\right)\right]-e^{-\frac{\tau}{L_j}}\left(\frac{1}{L_j}-\frac{\tau}{2Dt}\right)\times$$

$$\left.\times\left[1-\operatorname{erf}\left(\frac{\sqrt{Dt}}{L_j}-\frac{\tau}{2\sqrt{Dt}}\right)\right]\right\} \quad (12)$$

Formula (10) is analogous to the one given in reference (9), while formula (11) is similarly related to those found in references (8) and (10).

Formula (10) becomes formula (5) for time t sufficiently large so that $L_j \ll \sqrt{\frac{Dt}{2}}$. Using the asymptotic concept embodied in the [1 - erf (x)] function, we can show that formulas (11) and (12) likewise become formula (5) for $L_j \ll \sqrt{Dt}$.

Thus, rough estimates of the behavior of the time-dependent neutron distribution function for large t can be obtained with the aid of formulas (5) and (6).

As is evident from formula (6), the time of arrival of the thermal neutron wave maximum depends both on the hydrogen content in the rock (through parameter D) and the mineral content of the fluid filling the stratum (through parameter τ). Formula (5) shows that as t increases, the decline of the curve practically ceases to depend on D and will basically be determined by the exponential factor $e^{-t/\tau}$ which depends only on τ.

Determining τ according to the decline of the n(r,t)

curve, and having measured t_{max} it is possible to determine parameter D from formula (6).

Thus, this method affords a means of determining D and τ separately -- something which is impossible to do by means of stationary neutron sources.

Recalling that the coefficient of neutron diffusion basically depends on the hydrogen content of the rock (i.e. on the petroleum or water content of the stratum), while the mean life of the thermal neutrons in the layer is determined by the hydrogen content, and, to a much greater extent, by the mineralization of the stratum water due to its chlorine content, then this method will obviously provide a technique of solving problems on the determination of hydrogen content (porosity) of the stratum and the nature of the fluid filling the layer (petroleum or water).

For purposes of illustration, Figure 1 shows the n(r,t) curves constructed by means of formula (5) for r = 15 centimeters in a homogeneous sandstone medium of 20% porosity filled with petroleum (curve 1) or water containing 200 grams/liter of NaCl (curve 2).

As can be easily seen, for $\tau_{petroleum} = 5,7 \times 10^{-4}$ seconds and $\tau_{water} = 2,5 \times 10^{-4}$ seconds (i.e., differing by one-half) the difference in the thermal neutron densities in the rocks will be on the order of 10 after 10^{-3} second.

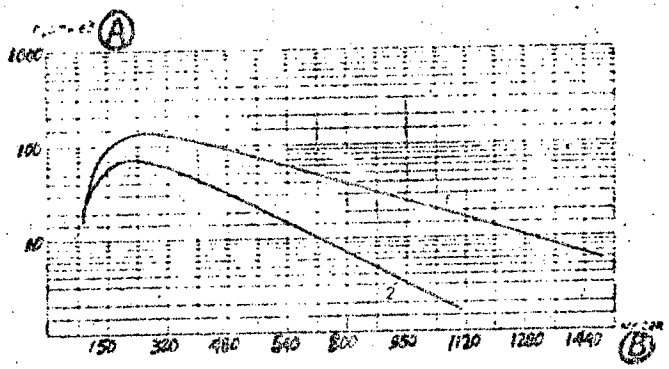


Figure 1. Calculated curves showing the dependence of thermal neutron density on time in a homogeneous sandstone medium of 20% porosity.

A = relative units; B = microseconds.

1 = Water-filled sandstone.

2 = Sandstone filled with mineral-containing water (200 grams/liter).

Thus, the pulsed method will permit us, according to all expectations, to determine the location of the water-petroleum contact level by means of greater effects (reaching several hundred percent) in cases involving stratum waters with a high mineral content, as well as to solve this problem with less accuracy under conditions of medium and low mineral content in the waters occurring below the petroleum layer.

Also of great importance is the fact that as time t increases, the total number of neutrons striking the indicator will be constituted to an ever greater extent by neutrons emerging from the more distant depths of the medium. Consequently, the slope of the n(r,t) curve with increasing t corresponds to the parameter γ for layers lying an ever greater distance from the indicator. This means that by increasing t, it is possible to increase considerably the penetrability of the method, and perhaps to a great extent eliminate the hindering effect of the parameters for the adjacent media (the steel column and fluid in the bore and cement lining). This is further aided by the fact that the mean life of thermal electrons γ in the neighboring media (and in the bore-hole itself) is considerably smaller than in the rock structure.

Experimental Data

In order to test the validity of the above suppositions, a series of experiments was conducted on rock strata models. The models used are described in (6).

The model constructed out of a mixture of sand and paraffin corresponded to sandstone of 20% porosity saturated with petroleum; the model consisting of a mixture of sand, paraffin, and sodium chloride corresponded to sandstone of the same porosity filled with water containing 200 grams of salt per liter. The axial opening of each model was fitted with a steel casing column and cement lining; the cement lining for the water-bearing sandstone model contained salts just as in actual practice (6).

An accelerating deuteron tube with a tritium target was used as the neutron source. Periodically -- 300 times each second -- the tube emitted short (5×10^{-5} second) bursts of neutrons of 14.1 million-electron-volt energies. The thermal neutrons were registered by means of a proportional counter with BF_3. Pulses from the counter were fed

into a 100-channel time analyzer [see Note]. The dimensions of the models, including target and counter positions are shown in Figure 2. [Note: The experiments were conducted at the Physics Institute imeni Lebedev of the USSR Academy of sciences.]

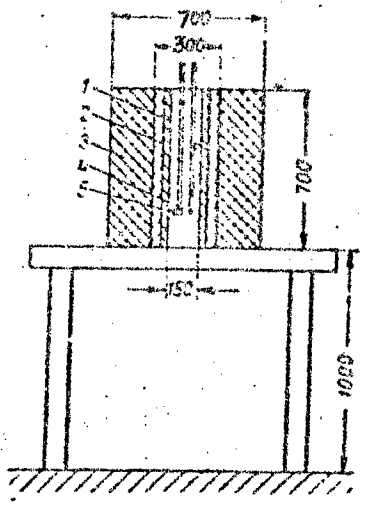


Figure 2. Diagram of the Experimental Set-Up.
1 = Steel casing column.
2 = Cement lining.
3 = Rock duplication medium.
4 = Thermal neutron counter.
5 = Target.

The results of measurements of the dependence of thermal neutron density on time t are shown in Figure 3. From these data it follows that for t = 800 microseconds, the indicator readings for the petroleum- and water-containing strata intersected by a dry bore-hole differ from each other by a factor of 10. Although the absolute values for $\tau_{petroleum}$ and τ_{water} obtained in this experiment (approximately 250 and 150 microseconds, respectively) differ from the calculated values (570 and 250 microseconds), apparently due to the relatively small size of the models and the consequent neutron leakage through the walls, and also because of the effects of the cement lining and steel casing tube, these data are fully adequate for making estimates of relative effects under actual conditions by means of the $\frac{\tau_{petroleum}}{\tau_{water}}$ and $\frac{n_{petroleum}}{n_{water}}$ ratios.

The counting speed in the salt-free sandstone model (at a mean intensity of ~10^6 neutrons/second for the stream of fast neutrons emitted by the accelerator-tube) after t = 800 microseconds amounted to about 5 counts per minute at a recording channel width of 10 microseconds. Such a counting speed makes it possible to make continuous measurements in bore-holes.

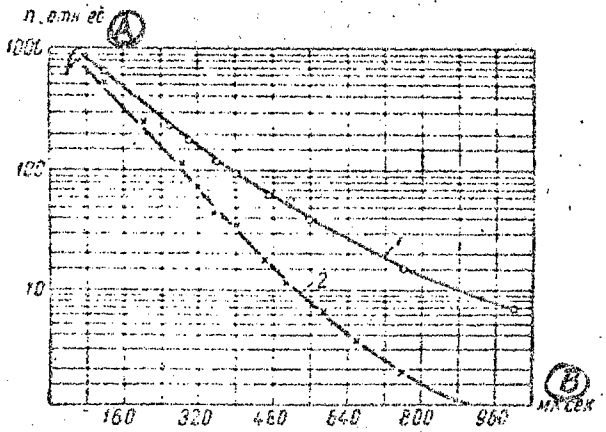


Figure 3. Experimental Curves Showing the Dependence of Thermal Neutron Densities on Time, Obtained From the Models of Water- and Petroleum-Bearing Sandstones Intersected by Cased Bore-Holes.
A = Relative units; B = Microseconds.
1 = Petroleum-filled sandstone.
2 = Sandstone filled with mineral-containing water (200 grams/liter).

Conclusion

The results of preliminary experiments presented in the present article show, first of all that the theoretically predicted differences in indicator readings as taken against water- and petroleum-containing strata can actually be obtained under bore-hole measurement conditions.

Secondly, the analysis of the results provides a means of determining the magnitudes of the basic pulsed neutron generator parameters, necessary for making such measurements, as the following: the mean neutron emission

is not less than 10^6 neutrons/second for pulses lasting 100-200 microseconds and sequence frequency not exceeding 400 cycles per second.

In order to obtain precise quantitative data on the possibilities of independently determining the rock parameters D and β as examined in the present article, and also to secure a considerable increase in the penetrability of the tests, detailed experiments are presently being conducted at the Petrology Institute of the USSR Academy of Sciences, using the laboratory neutron generator designed at this Institute. [see Note]. [Note: The description of the laboratory generator is given in the article entitled "A Laboratory Neutron Generator" by B.G. Yerozolimskiy and L.P. Voytsik in the present volume.]

Bibliography

1. Alekseyev, F.A., "The Present State and Future Outlook for the Application of Radiometric Techniques for Prospecting and Surveying Oil Fields", in the collection "The Use of Radioactive Isotopes and Radiation in the Petroleum Industry", Gostoptekhizdat, 1957.
2. Vlasov, N.A. "Neutrons", Gostoptekhizdat, 1955.
3. Dakhnov, V.N., "The Achievements of Our National Science and Industry in the Field of Applying Radioactive Methods to Prospecting, Surveying, and Developing Useful Mining Grounds", Trudy Vsesoyuznoy nauchno-tekhnicheskoy konferentsii po primeneniyu radioaktivnykh i stabil'nykh izotopov i izlucheniy v narodnom khozyaystve i nauke. Razvedka i razrobotka poleznykh iskopayemykh (Reports of the All-Union Scientific-Technical Conference on the Applications of Radioactive and Stable Isotopes and Radiation to the National Economy and Sciences. Surveying and Exploitation of Useful Mining Grounds), Gostoptekhizdat, 1958.
4. Yerozolimskiy, B.G., Voytsik, L.P., Popov, N.V., Shkol'nikov, A.S., "New Methods for Logging Bore-Wells Based on the Use of Pulsed Neutron Sources", Neftyanoye Khozyaystvo (Petroleum Industry), No 11, 1958.
5. Kantor, S.A. "Fundamentals of the Neutron Core Sampling Theory", in the collection "Prikladnaya Geofizika" (Applied Geophysics), issue 13, Gostoptekhizdat, 1955.
6. Kukharenko, N.K., Serdiy, A.G., Odinokov, V.P., "The Separation of Water- and Petroleum-Bearing Strata and

Determination of the Water-Petroleum Contact Level Under the Conditions of Cased Bore-Wells by the Neutron Beta-Gamma Method With Scintillation Counter and the Neutron-Beta Technique" in the collection "The Use of Radioactive Isotopes and Radiation in the Petroleum Industry", Gostoptekhizdat, 1957.

7. Flerov, G.N., Alekseyev, F.A., Yerozolimskiy, B.G. "Outlook for Using Radioactivity Methods in Geology for Prospecting and Surveying Useful Mining Gounds" Trudy vsesoyuzn... [see entry #3 above], Gostoptekhizdat, 1958.
8. Shimelevich, Yu.S. "Methodology for the Radioactive Analysis of Rocks Under Bore-Hole Conditions" Trudy vsesoyuzn.. [see entry #3 above], Gostoptekhizdat, 1958.
9. Iyengar, S.B.D., and Mani, G.S. (1955), Proceedings of the Indian Academy of Sciences, Vol XLII, No 4, Sec A, 1955.
10. Sykes, J., Nuclear Energy, 1955, 2, No 1, pp 31-37.

A 100-KV HIGH-VOLTAGE POWER SUPPLY FOR A BORE-WELL NEUTRON GENERATOR

-USSR-

[Following is the translation of an article by D.F. Bespalov and A.I. Khaustov in "Yadernaya Geofizika" (Nuclear Geophysics), Moscow, 1959, pages 346-350.]

The operation of the bore-well neutron generator accelerator-tube requires a power supply capable of providing a 100-kv (kilovolt) voltage at currents of up to 150-200 microamperes.

In view of the conditions under which it is to function, the power supply must conform to definite requirements as regards its dimensions; the device must be enclosed in a tube with an outside diameter not exceeding 100 millimeters and about 1 meter in length.

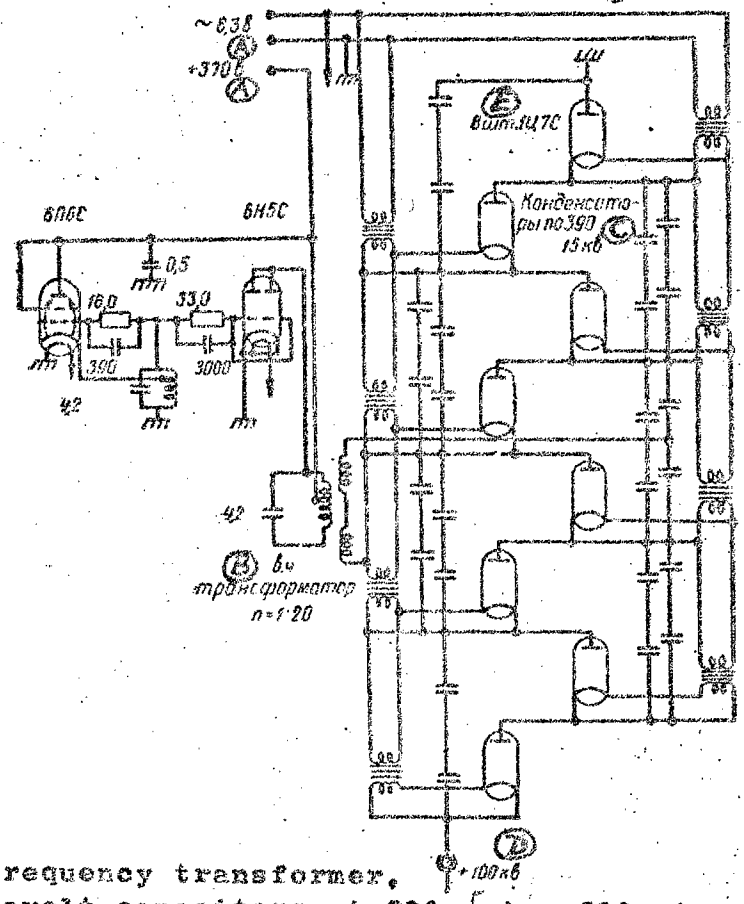
Using low-frequency alternating current (50-400 cycles per second) to feed the transformer of the high voltage rectifier, it is practically impossible to construct a high-voltage power supply of the required dimensions, since both the transformer and the filtering capacitors would have to be large.

For this reason it would be expedient to employ a circuit with a high-frequency (20-50 kilocycle) generator giving a voltage of about 10-15 kilovolts on the high-frequency tranformer secondary, which is then rectified and undergoes voltage multiplication.

This type of circuit would allow the use of small-capacitance miniature condensers and miniature kenotrons. The drawbacks of such a circuit are its relative complexity and comparatively low efficiency. When constructed of high-quality components, however, such a power supply operates with full reliability, without inordinate power consumption.

Figure 1 represents a schematic diagram for such a power supply, conceived and tested by the authors at the nuclear geology and geophysics laboratory of the USSR Academy of Sciences Institute of Petrology.

The high-frequency power supply unit is a resonance power amplifier with external excitation [see Note]. Such a sinusoidal voltage generator is more efficient than a pulse generator. The anode circuit of the power supply includes a high-frequency transformer with both windings adjusted to the working frequency; the capacitance of the secondary circuit consists of the capacitance of the winding itself and that of the multiplier-circuit component array. [Note: External excitation is employed in order to facilitate the adjustment and regulation of the supply unit; a self-exciting circuit could have been used, however.]



A = Volts.
B = High-frequency transformer.
C = 15-kilovolt capacitors at 390 [sic: 390 microfarads?]
D = Kilovolts.
E = Eight 1Ts7S kenotrons.
Figure 1. Schematic Diagram of High-Voltage Power Supply.

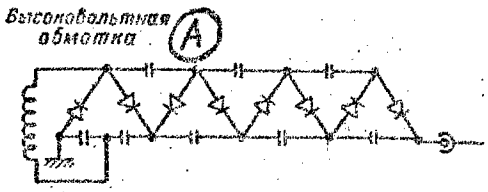
The choice of operating ranges for the power supply is based on the following considerations. In order to reduce the number of multiplier stages in the rectifier circuit, it is necessary to make the voltage on the transformer secondary as high as possible. The maximum feedback voltage for industrially-produced miniature kenotrons, however, does not exceed 30 kv (kilovolts), and because of this, the rectified voltage cannot be greater than 15 kv. In addition to this, the ratio of the voltage over the secondary circuit to the anode voltage of the generator is proportional to the ratio of the capacitances of the primary and secondary circuits. The capacitance of the secondary circuit is the the capacitance of the component array and cannot be made smaller than the order of tens of micromicrofarads (in this instance not less than 60 mmf); furthermore, the equivalent resistance of the secondary circuit falls as the capacitance of the primary circuit rises. Thus, to obtain a large output voltage, it is necessary to lower the equivalent resistance of the anode circuit and to employ low internal resistance tubes in the amplifier (such as the 6N5S-type tubes) capable of operating on low plate resistances.

The capacitance of the primary circuit likewise affects the choice of the operating frequency. It is expedient to make the operating frequency of the generator as high as possible, since this will allow the use of lower-capacitance condensers of commensurately smaller size in the rectifier. But equivalent resistance drops as the frequency increases at a given circuit capacitance. In the present circuit, a 20-kilocycle operating frequency was chosen for the generator.

The connection between the circuits was advisably made as strong as possible. For this purpose, the anode winding carries a large number of windings, only a part of which ($\frac{1}{3}$) were included in the anode circuit of the generator. The equivalent load resistance in this case is about 400 ohms.

At an alternating voltage amplitude of 15 kv, 8 multiplier stages are sufficient in the rectifier.

The adjustment of the power supply unit is accomplished according to the minimum plate current in the output cascade. In doing this, the capacitance of the plate (anode) circuit is chosen to obtain the greatest efficiency.



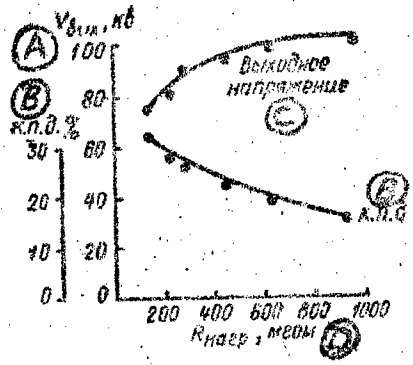
A = High-voltage winding.
Figure 2. Standard Rectifier Hookup.

The standard voltage-multiplier rectifier circuit (Figure 2) is of little use in the present case, since the component-array capacitance is that of the secondary circuit which carries the entire current of this circuit, thus creating a large voltage drop on the rectifier capacitors. For this reason the voltage provided by the last pair of kenotrons comprises about half of that provided by the first pair, and instead of an eight-fold voltage rise, we have only a six-fold voltage increase. More effective would be the connection of the secondary high-voltage transformer winding to the fourth multiplier stage rather than the first, as shown on Figure 1. In this case, the voltages provided by the two boundary kenotron pairs differ little from those provided by the intermediate pairs. One drawback of the circuit is the necessity for insulating the anode winding from the high-voltage winding which is under a 50-kv voltage relative to the chassis frame. But such a degree of insulation is quite easily achieved with the aid of a 5-millimeter layer of plexiglas.

The rectifier uses ITs7S-type kenotrons, for which the maximum feedback voltage is 30 kv. The kenotron filaments are supplied with a 400-cycle voltage from the distribution transformers. The higher frequency allowed a reduction of filament transformer dimensions.

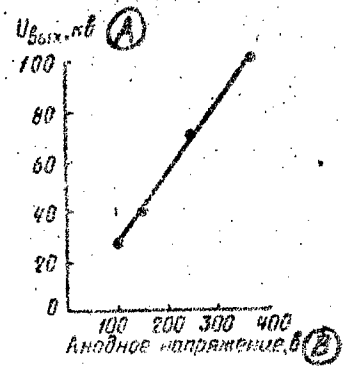
The circuit is mounted on plexiglas discs in a stacked configuration and separated by plexiglas posts. Since the distances between the circuit components are quite small, the possibility of spark-overs through the air is eliminated by placing the entire assembly in a vinylite jacket filled with transformer oil. The bottom of the jacket has an output binding strip. The high-voltage transformer windings are placed in a solid glued carcass made of plexiglas. The secondary windings of the kenotron heater distribution trans-

formers are similarly protected.



A = V_{output}, in kv.
B = Efficiency.
C = Output voltage.
D = R_{load}, in megohms.

Figure 3. Dependence of Output Voltage and Efficiency on Load Resistance.



A = V_{output}, in kv.
B = Plate voltage, in volts.
Figure 4. Dependence of Output Voltage on Plate Voltage.

The entire assembly is enclosed in a steel tube which increases the assembly capacitance and introduces significant losses into the high-frequency transformer. To reduce these losses, the transformer windings are positioned with their axis perpendicular to that of the tube. A copper screen in the place where the windings are mounted also affords some improvement.

The high-voltage power supply develops 100 kv with a 600 megohm load, i.e., has a power of about 17 watts. Operating at this level, it uses about 200-250 milliamperes

at 370 volts and is approximately 20% efficient. The internal resistance of the power supply unit is relatively low; because of this, the output voltage depends little on the load, while the efficiency rises with decreasing load resistance (Figure 3).

The output voltage varies in direct proportion to the plate voltage (Figure 4). This permits easy regulation of the high output voltage; to obviate changes in the output voltage as a result of arbitrary fluctuations in the plate voltage, however, it is necessary to stabilize the latter.

The circuit can also be modified to include a negative feedback hookup to stabilize the output voltage.

In the future, the dimensions of the power supply unit may be reduced.

This high-voltage power supply can be used successfully for driving accelerator tubes for both bore-well and small-size laboratory neutron generators.

A MINIATURE SEALED NEUTRON TUBE

-USSR-

[Following is the translation of an article by B.G. Yerozolimskiy, L.N. Bondarenko, L.P. Voytsik, Yu.S. Shimelevich, and L.I. Yudin in "Yadernaya Geofizika" (Nuclear Geophysics), Moscow, 1958, pages 351-355.]

Experimental studies conducted for the purpose of examining the possibilities of designing a miniature neutron generator intended for use in bore-well logging were initiated at the Petrology Institute of the USSR Academy of Sciences in 1957.

The central component in a neutron generator is the ionic accelerator tube. A choice of design for this device basically determines the solutions to a whole series of technical problems involved in the development of a miniature bore-hole neutron generator.

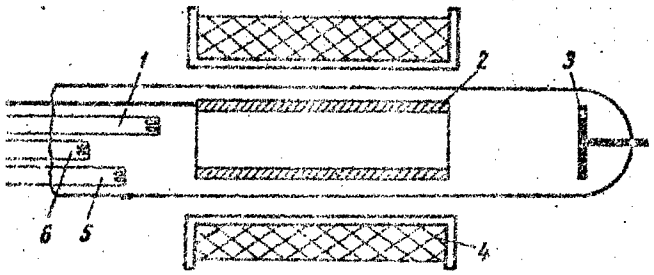


Figure 1. Schematic Diagram of Miniature Sealed Neutron Tube.

A schematic diagram of the described tube is shown in Figure 1.

Electrons emitted by the heated tungsten cathode 1 are accelerated by the cylindrical anode 2 and move through it along spiral paths as a result of the longitudinal magnetic field H set up by coil 4 which carries direct current.

If a negative potential V_3 relative to the cathode is applied to electrode 3, then prior to reaching cylinder 2, the electrons will be reflected, thus vibrating within the cylinder and thereby ionizing the gas which fills the tube. The positively-charged ions, pulled in by the field of electrode 3 and accelerated up to energy V_3, strike a target located within electrode 3.

Thus, the design shown on Figure 1 represents a simple combination of a vibrating electron-discharge ion source with an accelerator tube having a singe acceleration gap.

A careful examination of the design revealed, however that it was capable of performing yet another function -- namely, that of a high-voltage kenotron which could be used to double the accelerating voltage.

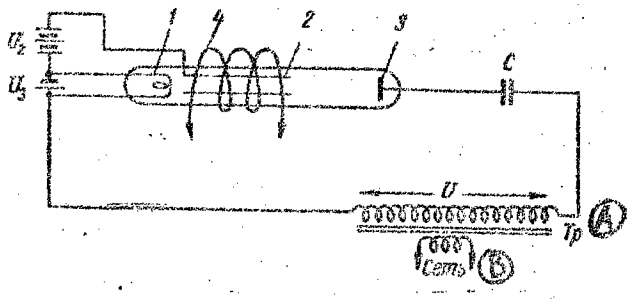


Figure 2. Schematic Diagram of Voltage-Doubling Circuit in Sealed Neutron Tube.

A = High-voltage transformer.
B = Circuit voltage.
1 = Heated tungsten cathode.
2 = Cylindrical anode.
3 = Electrode with target.
4 = Coil which sets up longitudinal magnetic field.
U_2 = Cylindrical anode potential current source.
U_3 = Tungsten cathode heating-current source.
C = Capacitance.

Actually, even if just a small positive voltage is applied to electrode 3, then the electrons will cease to be reflected, the vibrational character of their motion will

stop, and the electron current will flow toward electrode 3, which in this case will play the role of anode, as in the standard kenotron.

The simplest electronic circuit employing the above-mentioned combination of ionic acceleration tube and high-voltage kenotron functions is illustrated in Figure 2.

This is the usual voltage-doubling circuit making use of capacitance C and the kenotron; the role of the latter is played by the tube itself. If the magnitude of the ionic current J_{ion} in the tube (with electrode 3 negative) is smaller than the electron current J_{el} at electrode 3 (with electrode 3 positive), then the capacitance C will receive a charge practically equal to the amplitudinal value of the voltage U across the secondary winding of the high-voltage transformer (A), and the voltage across electrode 3 will pulse from a small positive, down to an almost double negative value (Figure 3).

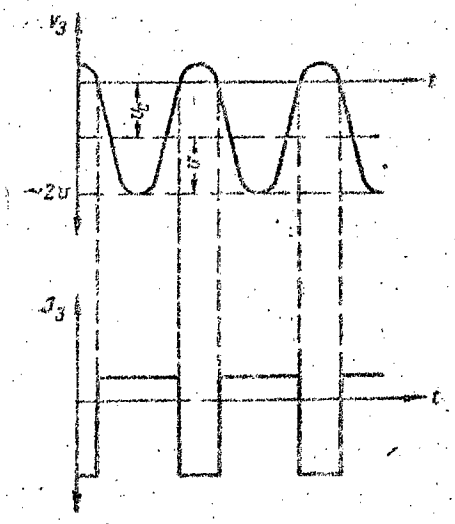


Figure 3. Plot of Potentials and Currents Across Electrode and Target 3 as They Depend on Time.

As this happens, as can be seen from the diagram for current J_3 flowing toward electrode 3, the ionic current will flow almost continuously, while the electron current will flow only during those relatively short time intervals when potential V_3 is positive.

It is inadvisable, however, to have the ionic current flowing toward the target while potential V_3 is considerably smaller than maximum, since this will not increase the emission of neutrons and will create an excessive load both across the transformer and the target. For this reason, the direct-current voltage supply U_2 (Figure 2) is replaced in the circuit with a special pulse genrator which is synchronized with the alternating-current voltage across the transformer in such a way that its positive pulses fed to cylinder 2 induce the appearance of electron and ionic flow only during short time intervals close to the moments of maxima for voltage V_3 (Figure 4).

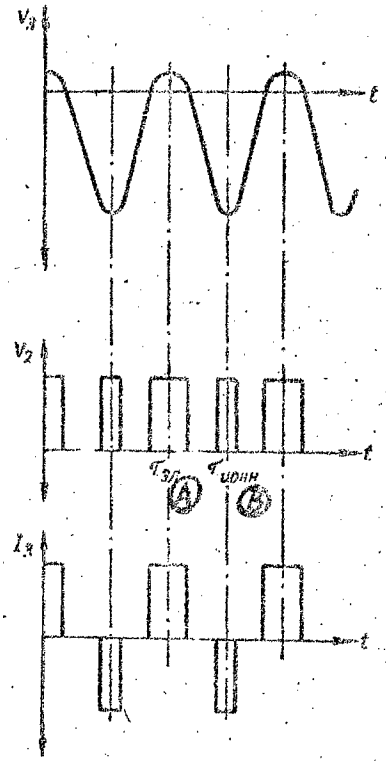


Figure 4. Plot of Potentials and Currents Across Electrode and Target 3 Against Time With the Inclusion in the Circuit of a Pulse Generator Across the Cylindrical Anode. A = Telectron; K = Tion.

As may be seen from Figure 4, the ionic current flows only at such times when the voltage across electrode 3 is close to its maximum negative value (and is practically

equal to double the amplitudinal voltage across the transformer).

The tube design just described is extremely convenient for the purpose of constructing a bore-hole neutron generator, inasfar as the high-voltage source, the transformer, can be used without a separate kenotron for doubling the voltage.

As follows from the description, the operating cycle for such an accelerator-tube is of a pulse type with pulse duration τ_{imp} determined by the pulse generator; the sequential frequency of the pulses is equal to the frequency of the alternating-current voltage across the transformer.

In the prototype of the tube which was actually constructed, the working voltage was chosen as 100-120 kv. The operation of the tube consequently requires a transformer with a 60 kv peak voltage. Such a transformer was constructed to fit into a tube having a diameter ~100 millimeters.

The target in the tube was made of tritium-impregnated zirconium; the tube contained deuterium under a pressure of $5 \cdot 10^{-4}$ millimeters of mercury.

Under such a pressure the gap between cylinder 2 and electrode 3, which is on the order of several centimeters, is able to withstand a voltage of up to 150 kv.

The magnitude of the ionic current, which may be obtained in a tube of the described design at a pressure of $3\text{-}5 \times 10^{-4}$ millimeters of mercury, reaches several milliamperes; the neutron output may be as high as 10^7 neutrons/second.

Optimum current values were obtained by a proper choice of length and diameter for cylinder 2, as well as of a power supply operating range, i.e., the magnitude of the magnetic field H, the cathode emission current, and the pulse voltage amplitude V_2 across the cylinder.

One of the important problems involved in designing a bore-hole neutron generator is that of maintaining the proper pressure in the tube.

In the initial stage of work on the project, A.S. Shkol'nikov, research fellow (aspirant) at the Petrology Institute completed a detailed study of the various possible evacuation systems which could be used in a deep bore-hole apparatus.

In particular, good results were obtained with a small

diffusion pump featuring a trap and semiconductor cooling. The main attention in this study was devoted, however, to rarefaction with the aid of heated titanium wire samples.

It is also necessary to point out that the tube design described above incorporates an equal gas pressure at all interior points in the tube (both in the acceleration gap and the ion source); this eliminates the leakage of gas in the tube, which necessarily occurs in standard neutron generators where gas pressure at the source must be 10^{-1} - 10^{-3} millimeters of mercury, to a significant degree.

The absence of intense gas leakage naturally simplifies the problem of maintaining the correct pressure in the tube.

It turned out that in a well-evacuated and sealed gas tube in which all electrodes, except, of course, the target, are also well degasified, the vacuum gradually improves during operation (i.e., the tube becomes "tinned") as a result of the ionic evacuation mechanism.

Even pressure depends on the working temperature of the tube, as well as on the operating range (the mean magnitude of the ionic current and the energy of the accelerated ions), although as a rule it is several times smaller than is required. This is why a titanium wire spiral impregnated with deuterium is welded on inside the tube (labeled 5 in Figure 1).

Heating the spiral to a given temperature (by adjusting the current passed through it), it is possible to maintain the required deuterium pressure in the interior of the tube.

The method here employed is analogous to the method of maintaining the working gas pressure in hydrogen thyratrons.

10,106

-END-